ARE THERE ANY STARS LACKING NEUTRON-CAPTURE ELEMENTS?
EVIDENCE FROM STRONTIUM AND BARIUM

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ABSTRACT

The cosmic dispersion in the abundances of the heavy elements strontium and barium in halo stars is well known. Strontium and barium are detected in most cool, metal-poor giants, but are these elements always detectable? To identify stars that could be considered probable candidates for lacking these elements, I examine the stellar abundance data available in the literature for 1148 field stars and 226 stars in dwarf galaxies, 776 of which have metallicities lower than [Fe/H] < −2.0. Strontium or barium have been detected in all field, globular cluster, and dwarf galaxy environments studied. All upper limits are consistent with the lowest detected ratios of [Sr/H] and [Ba/H]. The frequent appearance of these elements raises the intriguing prospect that at least one kind of neutron-capture reaction operates as often as the nucleosynthesis mechanisms that produce lighter elements, like magnesium, calcium, or iron, although the yields of heavy elements may be more variable.

Subject headings: galaxies: dwarf — globular clusters: general — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: Population II

1. INTRODUCTION

It is now well established that there exists a cosmic star-to-star dispersion in the abundances of the heavy elements barium and strontium in halo field stars. Early hints of this effect appeared in the work of Gilroy et al. (1988) and Magain (1989), and subsequent work by Ryan et al. (1991, 1996), McWilliam et al. (1995), McWilliam (1998), Burris et al. (2000), and others confirmed and extended it to stars with metallicities 10,000 times lower than the Sun. These studies have repeatedly demonstrated that the dispersion cannot be a consequence of uncertainties in the abundance analysis techniques or other observational error. The lighter elements show more constant ratios with dispersions mostly consistent with observational error only (e.g., Arnone et al. 2005). The contrast between the light (e.g., magnesium) and heavy elements (e.g., strontium, barium, or europium) is apparent in the small dispersion of [Mg/Fe] ratios and the large dispersion of [Eu/Fe] ratios at low metallicity, as shown by Figure 14 in Sneden et al. (2008).

Many surveys, including those of Bond (1970, 1980), Bidelman & MacConnell (1973), Beers, Preston, & Shectman (1985, 1992), Frebel et al. (2006), Christlieb et al. (2008), and the Sloan Extension for Galactic Understanding and Exploration (Yanny et al. 2009) have been conducted to identify FGK-type stars that contain weak absorption lines from metals such as calcium or iron. Presumably such stars are among the oldest low-mass stars in the Universe, but to date no star has been found to be lacking magnesium, calcium, or iron. The elements heavier than the iron group ($Z > 30$ or so) are thought to be produced in different ways than the lighter elements are, likely by neutron-capture or charged-particle reactions. But, like the lighter elements, are the heavy ones always present?

The purpose of this paper is to examine the stellar abundance data available in the literature to consider whether any stars are currently known that may be considered probable candidates for lacking elements heavier than the iron group altogether. The specific nucleosynthetic origins of these elements are no doubt interesting, but instead I will focus on the more general question of detectability. Roederer et al. (2010b) considered how often Sr II or Ba II lines had been detected in one large snapshot survey of metal-poor stars, that of Barklem et al. (2005), who studied 253 stars. For the 34 coolest stars in their sample, those with $T < 4800$ K, Sr II and Ba II lines were detected in every one. In this paper, I reexamine this question by considering an expanded sample of field, globular cluster, and dwarf galaxy stars.

I adopt the standard definition of elemental ratios throughout this work. For elements X and Y, the logarithmic abundance ratio relative to the solar ratio is defined as $[X/Y] \equiv \log_{10}(N_X/N_Y) - \log_{10}(N_X/N_Y)_\odot$. These ratios always indicate the total elemental abundance after ionization corrections have been applied. For stellar metallicity, I adopt the iron abundance as derived from Fe II lines, when available, and otherwise I resort to the [Fe/H] values reported in the literature.

2. STRONTIUM AND BARIUM

Strontium (Sr, $Z = 38$) and barium (Ba, $Z = 56$) are the two elements heavier than the iron group best-suited for this investigation. Sr II and Ba II are the dominant species of these elements in late-type stellar atmospheres because of their low first ionization potentials, 5.69 and 5.21 eV, respectively. Both elements are members of the alkaline earth metals along with magnesium (Mg, $Z = 12$) and calcium (Ca, $Z = 20$). These ions all have a single valence s electron in the ground state. The first excited p state has $J = 3/2$ or $1/2$, giving rise to a strong resonance doublet feature. These transitions correspond to the well-known Mg II doublet at 2795 and 2802 Å (connecting the $2p^63s$ $^2S_{1/2}$ and $2p^63p$ $^2P^o$ terms) and the Ca II doublet at 3933 and 3968 Å ($3p^64s$ $^2S_{1/2}$

to $3p^6 4p \ ^2P^o$). These absorption lines frequently rank among the strongest lines observed in late-type stars and galaxies whose integrated light is dominated by old stellar populations. The Sr II doublet at 4077 and 4215 Å ($4p^6 5s \ ^2S_{1/2}$ to $4p^6 5p \ ^2P^o$) and the Ba II doublet at 4554 and 4934 Å ($5p^6 6s \ ^2S_{1/2}$ to $5p^6 6p \ ^2P^o$) are their analogs. Since strontium and barium frequently rank among the more abundant elements heavier than the iron group, these spectral lines are the most readily available heavy element transitions in the optical, near ultraviolet, and near infrared regions of stellar spectra.

The proportionally large abundance of barium makes it a better choice for comparison than europium ($Z = 63$). Europium is commonly used as a tracer of nucleosynthesis by the rapid neutron-capture process (r-process). A large fraction of its solar system abundance ($> 91\%$; e.g., Cameron 1982; Burris et al. 2000; Bisterzo et al. 2011) is attributed to r-process nucleosynthesis. In the solar system, barium is ≈ 46 times more abundant than europium. In metal-poor halo stars strongly enriched by r-process material, like CS 22892–052, barium is approximately nine times more abundant than europium (Sneden et al. 2003a). Metal-poor stars with a deficiency of elements heavier than barium, like HD 122563, have similar ratios of barium to europium, ≈ 10–15 (e.g., Honda et al. 2006; Roederer et al. 2012). Metal-poor stars highly enriched by material produced by slow neutron-capture reactions (the s-process) frequently show barium to europium ratios of several hundred or more (e.g., Aoki et al. 2002b). Barium is always considerably more abundant than europium, so it should be detectable more often than europium if the abundances of both elements are low.

In most metal-poor stars, the [Ba/Eu] ratio is low and close to the ratios found in CS 22892–052 and HD 122563 (e.g., Gilroy et al. 1988; McWilliam 1998). This indicates that even the barium in these stars owes its origin mainly to some kind of r-process nucleosynthesis. The strontium may owe its origins to several mechanisms in addition to r-process nucleosynthesis (e.g., Travaglio et al. 2004). I emphasize that the results of the present study do not require that either of these interpretations holds true.

3. LITERATURE DATA

I have compiled a sample of 1148 field stars and 226 stars in dwarf spheroidal (dSph) or ultra-faint dwarf (UFD) galaxies from the literature with reported detections or upper limits on the strontium or barium abundance. Of these, 728 (39) field (dSph and UFD) stars have reported detections or upper limits for both strontium and barium, 318 (187) stars have reported detections or upper limits for barium only, and 102 (0) stars have reported detections or upper limits for strontium only. A total of 707 (69) of these stars have [Fe/H] $<$ -2.0. The majority of the field stars in this compilation were originally identified as having weak metal lines in the spectroscopic surveys listed in Section 1 or as high proper motion stars in the surveys of Giclas, Burnham, & Thomas (1971, 1978). All of the abundances considered have been derived from spectra with moderately high resolution ($R \equiv \lambda/\Delta\lambda \sim 15,000$ or better). The complete list of 54 studies of field stars and 23 studies of dSph and UFD galaxy stars is given in the caption to Figure 1. Additional comments on a few stars can be found in Appendix A.

This compilation is surely not complete for the highest metallicities or for stars with high levels of heavy elements. For example, stars strongly enriched by the r-process or s-process are underrepresented. These are not the stars of interest here. Sr II and Ba II lines are always easily detectable in these stars, and the lines are often saturated.

Figure 1 illustrates the [Sr/H] and [Ba/H] ratios found in this sample of stars. Both detections and upper limits are included, although not all studies report upper limits for non-detections. The upper limits cited in the literature are frequently, but not always, 3σ upper limits. Strontium and barium abundances have not always been reported together, however, so Figures 2 and 3 display the [Sr/Fe] and [Ba/Fe] ratios as a function of [Fe/H].

I have made no attempt to correct these literature values to a common $\log(gf)$ or solar abundance scale or to standardize for different treatments of the Van der Waals damping constants, C_6. The transition probabilities of these lines are each well known to excellent accuracy. For example, the NIST Atomic Spectral Database (Kramida et al. 2012) grades their accuracy at 10% (0.04 dex) or better, and the variations in the $\log(gf)$ values adopted in the stellar abundance literature generally mirror this. Differences in the accepted solar abundances of these elements are also small, varying by ≤ 0.05 dex among frequently-cited reviews (Anders & Grevesse 1989; Lodders 2003; Asplund et al. 2009). Such differences are negligible for our purposes.

For consistency, all abundances considered in this study are based on one-dimensional model atmospheres assuming that local thermodynamical equilibrium (LTE) holds. Sr II and Ba II are the dominant species in the line-forming layers of FGK-type stars, so small departures from Saha ionization equilibrium will have little impact on the derived abundances. The resonance lines of Sr II and Ba II may be driven out of LTE population equilibrium (non-LTE) by underpopulating the lower levels and overpopulating the upper levels relative to their LTE Boltzmann equilibria. Both Sr II and Ba II behave similarly because of their similar electronic structures. Such departures are predicted to have a moderate impact on the derived abundances, and they are dependent on a variety of factors including the temperature, gravity, [Sr/H] or [Ba/H], and the collisional cross sections for hydrogen and electrons. At low metallicity, for a given [Sr/H] or [Ba/H] the resonance line profile calculated under non-LTE conditions is weaker than that calculated assuming LTE. Abundance differences up to $+0.3$ dex or $+0.4$ dex are predicted when calculated assuming non-LTE relative to the LTE case for most of the temperature and abundance ranges of interest here (Belyakova & Mashonkina 1997; Mashonkina et al. 1999; Short & Hauschildt 2006; Andrievsky et al. 2009, 2011). While these differences certainly are not negligible, for low [Sr/H] and [Ba/H] they will generally raise the abundances and detection thresholds (Section 4) together. This offset does not affect the conclusions of the present study.
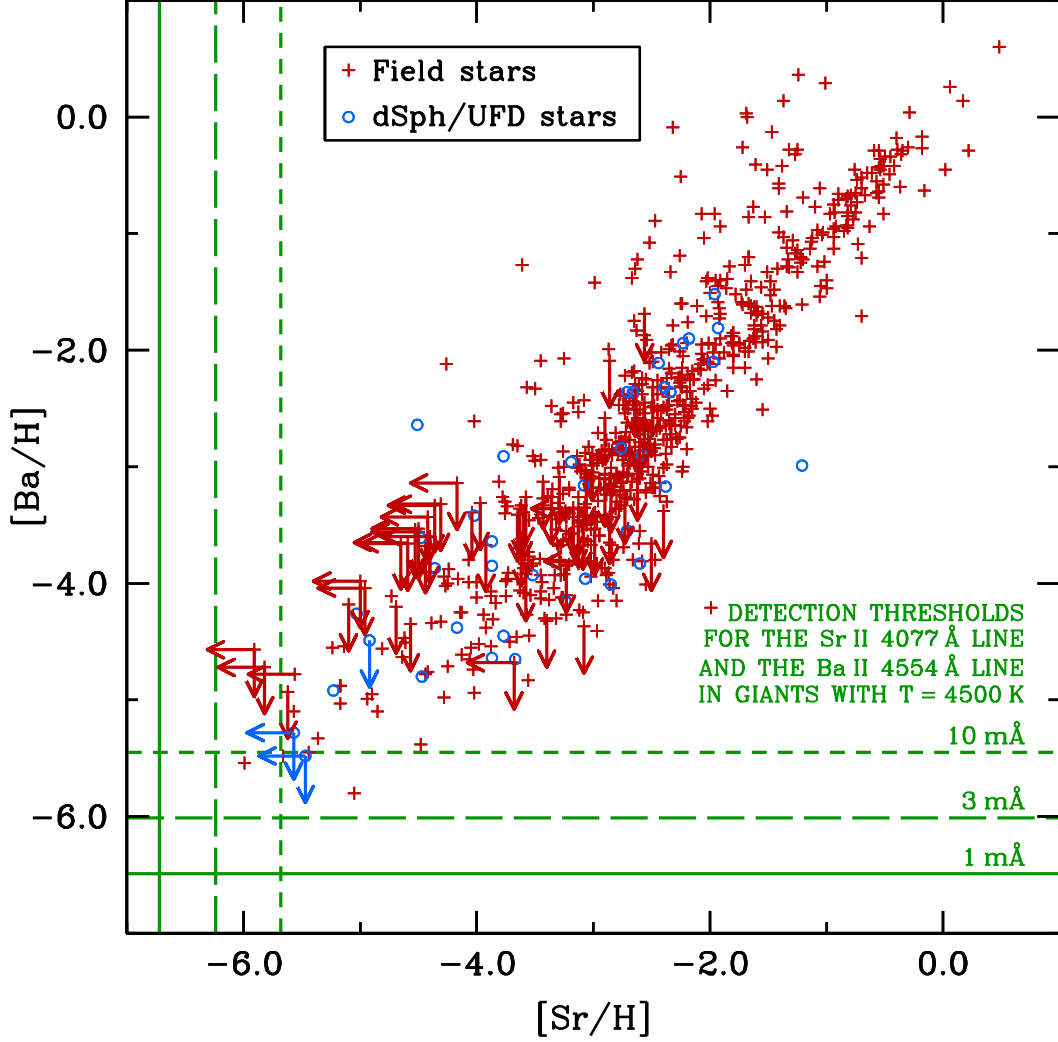
4. DETECTION THRESHOLDS

FIG. 1.— [Sr/H] and [Ba/H] ratios in field stars and dwarf galaxies. Approximate equivalent width detection thresholds for the Sr II 4077 Å line and the Ba II 4554 Å line in the atmosphere of a cool giant, assuming LTE, are shown by the sets of green curves. The data for the field stars are taken from the following sources: Andrievsky et al. (2011), Aoki et al. (2002a, 2004, 2005, 2006, 2009a, 2010, 2012), Bai et al. (2004), Barklem et al. (2005), Bonifacio et al. (2009), Burris et al. (2000), Caffau et al. (2012), Carretta et al. (2002), Christlieb et al. (2004), Cohen et al. (2004, 2006, 2008), Depagne et al. (2000), François et al. (2007), Fulbright (2000), Gratton & Sneden (1994), Hansen et al. (2011), Hollek et al. (2011), Honda et al. (2004, 2011a), Ishigaki et al. (2010), Ito et al. (2009), Ivans et al. (2003), Johnson (2002), Johnson & Bolte (2002), Jonsell et al. (2005), Lai et al. (2007, 2008, 2009), McWilliam et al. (1995), McWilliam (1998), Mishenina & Kovtyukh (2001), Nissen & Schuster (2011), Norris et al. (2000, 2001, 2007), Preston & Sneden (2000, 2001), Preston et al. (2006), Roederer et al. (2010a), Ryan et al. (1991, 1996, 1998), Sivarani et al. (2006), Sneden et al. (2003b), Spite et al. (2000), Stephens & Boesgaard (2002), and Yong et al. (2012). The data for the dSph and UFD stars are taken from the following sources: Aoki et al. (2007, 2009b), Cohen & Huang (2009, 2010), Cohen & Kirby (2012), Feltzing et al. (2009), Frebel et al. (2010a,b), Fulbright et al. (2004), Geisler et al. (2005), Honda et al. (2011b), Kirby & Cohen (2012), Koch et al. (2008), Lemasle et al. (2012), Letarte et al. (2010), Norris et al. (2010a,b), Sbordone et al. (2007), Shetrone et al. (2001, 2003), Simon et al. (2010), Tafelmeyer et al. (2010), and Venn et al. (2012).

I have computed approximate thresholds for detecting the stronger of the two resonance lines of each species, Sr II 4077 Å and Ba II 4554 Å, in representative model atmospheres ranging from cool giants ($T = 4500$ K, $\log g = 0.5$, and $v_t = 2.0$ km s^{-1}), to stars on the lower giant branch ($T = 5500$ K, $\log g = 3.5$, and $v_t = 1.5$ km s^{-1}), to warm turn-off stars ($T = 6400$ K, $\log g = 4.0$, and $v_t = 1.3$ km s^{-1}). These calculations are made using models interpolated from the α-enhanced grid of ATLAS9 model atmospheres (Castelli & Kurucz 2003) and the latest version of the analysis code MOOG (Sneden 1973) with updates described in Sobeck et al. (2011). The overall metallicity of the model has little effect (± 0.07 dex) on the calculated limits of [Sr/H] or [Ba/H].

The continuous opacity is lower in cooler giants than in warm turn-off stars, so absorption lines will be easier to detect in cooler stars for a constant [Sr/H] or [Ba/H]. In warmer stars, the threshold levels increase. For example, the 3 mÅ detection threshold for the Sr II 4077 Å line in the model with $T = 4500$ K is [Sr/H] ≈ -6.2. In the model with $T = 5500$ K, the same 3 mÅ detection threshold is [Sr/H] ≈ -4.5, while in the model with $T = 6400$ K it is [Sr/H] ≈ -3.8. Similarly, the 3 mÅ detection threshold for the Ba II 4554 Å line in the model with $T = 4500$ K is [Ba/H] ≈ -6.0. In the model with $T = 5500$ K it is [Ba/H] ≈ -4.3, while in the model with

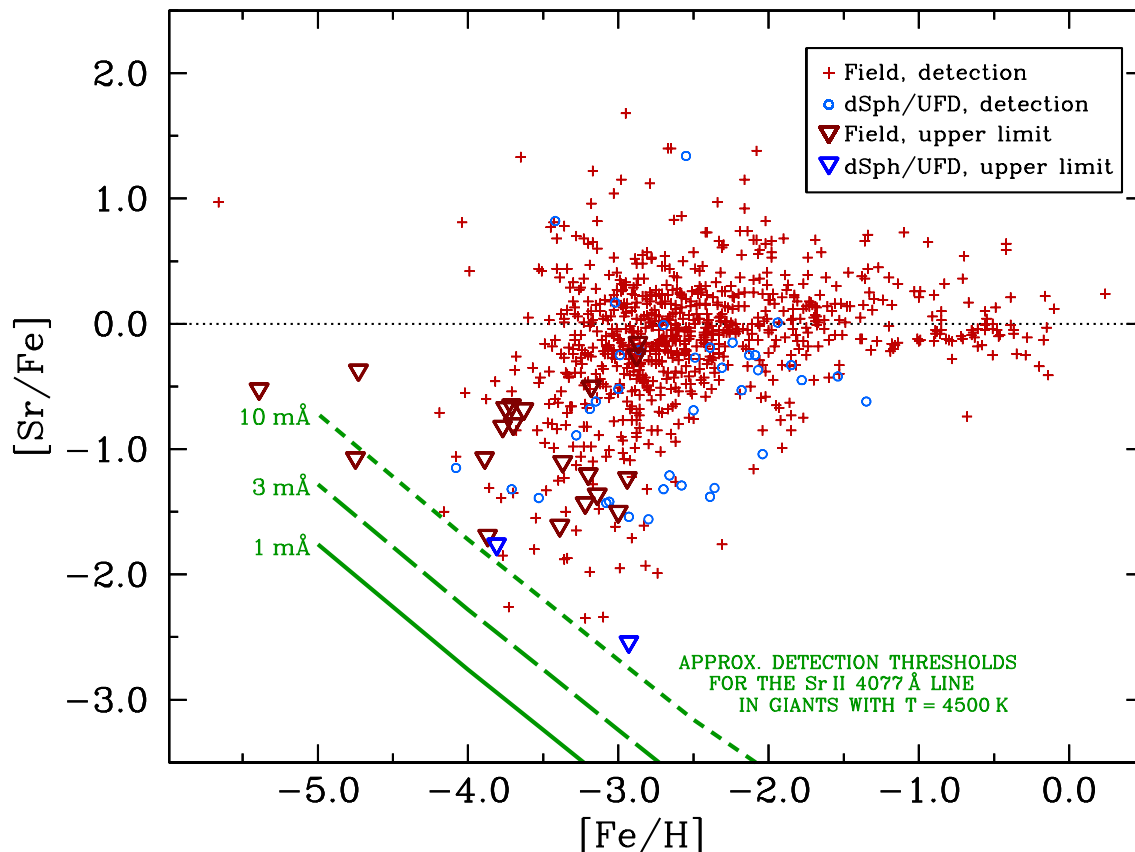FIG. 2.— [Sr/Fe] ratios in field stars and dwarf galaxies. Approximate equivalent width detection thresholds for the Sr II 4077 Å line in a cool giant atmosphere, assuming LTE, are shown by the set of green curves. The dotted line marks the solar [Sr/Fe] ratio. Literature sources for the data are listed in the caption to Figure 1.

$T = 6400$ K it is [Ba/H] ≈ -3.5. The 10 mÅ, 3 mÅ, and 1 mÅ detection thresholds for cool giants are illustrated by three sets of lines in Figures 1–3. These represent the lowest levels of strontium or barium that could be detected under favorable circumstances.

The Ba II 4554 Å line is broadened by the energy level shifts from different isotopes of barium, and the levels of the two naturally-occurring odd-A isotopes are further broadened by hyperfine splittings. For weak lines on the linear portion of the curve of growth, neglecting this effect has no significant impact on the derived abundances. This is illustrated by the low barium abundance cases in Figure 1 of McWilliam (1998).

5. STRONTIUM AND BARIUM IN GLOBULAR CLUSTERS

Heavy element abundance trends in globular cluster stars generally reflect the patterns in field stars at comparable metallicities. Globular clusters belonging to the Milky Way and its system of dwarf galaxies all have mean metallicities [Fe/H] > -2.6 or so. At these metallicities, the highly-enriched and highly-deficient extremes of neutron-capture enrichment found in more metal-poor Galactic halo stars are generally muted in both field stars and globular clusters (e.g., Gratton et al. 2004). Heavy elements are not always studied in late-type stars in globular clusters. In studies using modern instrumentation (since about 1990), no upper limits have been published indicating any element, X, heavier than the iron group has [X/Fe] < -1 in globular clusters (see, e.g., the com-

pilation by Pritzl et al. 2005). Some clusters show an internal star-to-star dispersion in [X/H] or [X/Fe], but they are always present (e.g., Norris & Da Costa 1995; Sneden et al. 1997; Yong & Grundahl 2008; Roederer 2011). The heavy elements are detected even in extreme outer halo clusters that reside at great distances, like Pal 3, Pal 4, Pal 14, or NGC 2419 (Koch et al. 2009; Koch & Côté 2010; Çalışkan et al. 2012; Cohen & Kirby 2012). Stars in globular clusters associated with the Sagittarius (e.g., Brown et al. 1999) and Fornax (Letarte et al. 2006) dwarf galaxies consistently show the presence of heavy elements, as do those associated with the the Large Magellanic Cloud (Johnson et al. 2006; Mucciarelli et al. 2008, 2010).

There appear to be no globular cluster environments that were lacking in the elements heavier than the iron group when the present-day stars were forming. Since these elements are always found in ∼ solar ratios in globular clusters, they are not shown in the figures.

6. STRONTIUM AND BARIUM IN FIELD STARS AND DWARF GALAXIES

Figure 1 shows the [Sr/H] and [Ba/H] ratios in metal-poor field stars and dwarf galaxies, and Figures 2 and 3 show the [Sr/Fe] and [Ba/Fe] ratios as a function of [Fe/H]. These figures reveal that the number of stars where strontium and barium are examined but not detected (i.e., upper limits are reported) constitute only a small fraction of all metal-poor stars that have been
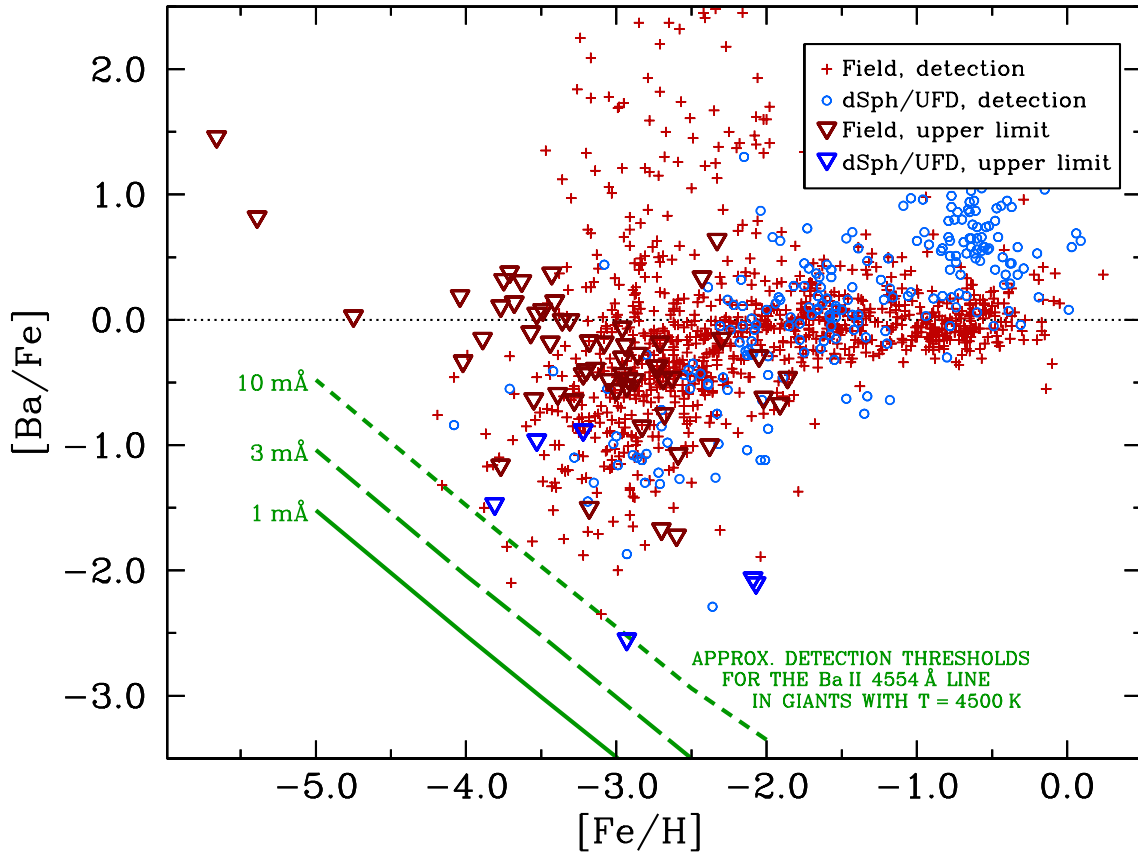
FIG. 3.— [Ba/Fe] ratios in field stars and dwarf galaxies. Approximate equivalent width detection thresholds for the Ba II 4554 Å line in a cool giant atmosphere, assuming LTE, are shown by the set of green curves. The dotted line marks the solar [Ba/Fe] ratio. Literature sources for the data are listed in the caption to Figure 1.

studied. Figures 2 and 3 demonstrate that many stars show subsolar [Sr/Fe] and [Ba/Fe] ratios at metallicities below [Fe/H] = −2.5. This, of course, has been found repeatedly by many of the studies whose results are incorporated into the present sample.

The stars of most interest for this study are those in the lower left corner of Figure 1 with the lowest [Sr/H] and [Ba/H] ratios. At present, there are no upper limits on [Sr/H] or [Ba/H] for field stars that are lower than the lowest levels of detection. HE 1116−0634, studied by Hollek et al. (2011), shows detectable Sr II and Ba II lines and a [Sr/H] ratio (−5.99 ± 0.15) lower than any other stars studied at present. Sr II and Ba II lines are also detected in HE 0302−3417, also studied by Hollek et al., which has a [Ba/H] ratio (−5.80 ± 0.15) lower than any other stars studied at present. Both of these stars are extremely cool (4400 K), facilitating the detection of these weak lines.

In the dwarf galaxy sample, there are two stars with upper limits on [Sr/H] and [Ba/H] that are almost as low as the lowest detections in field stars, Star 119 in Draco (Fulbright et al. 2004) and Star 1020549 in Sculptor (Frebel et al. 2010b). Four field stars, CS 30336–049 (Lai et al. 2008; Yong et al. 2012), BS 16084–160 (Aoki et al. 2005), CS 22968–014 (McWilliam et al. 1995; McWilliam 1998; François et al. 2007), and CS 30325–094 (Aoki et al. 2005; François et al. 2007) show detectable Sr II and Ba II lines and [Sr/H] and [Ba/H] ratios comparable to the lower limits found in

the two dwarf galaxy stars. These stars can all be found in the lower left corner of Figure 1 with [Sr/H] and [Ba/H] = −5.5 ± 0.3.

Several independent investigations by Shetrone et al. (2003), Geisler et al. (2005), and Kirby & Cohen (2012) have detected Sr II and Ba II lines in numerous other stars in Sculptor ($M_V = −11.1$), including one star with [Fe/H] = −4.0 (Tafelmeyer et al. 2010). Draco ($M_V = −8.8$) is not completely devoid of heavy elements, either; Shetrone et al. (2001) and Cohen & Huang (2009) have detected Sr II and Ba II lines in other stars in Draco. Stars 2 and 3 in Hercules ($M_V = −6.6$) show low upper limits, [Ba/H] < −4.2 ([Ba/Fe] < −2.1; Koch et al. 2008). Sr II and Ba II lines have been detected in other stars in Hercules (François et al. 2012; Koch et al. 2012; A. Koch, 2012, private communication), so Hercules is also not completely lacking heavy elements.

Frebel & Bromm (2012) point out that a galaxy like Draco is luminous enough to have possibly been assembled from several "first" galaxies, some of which may not have experienced any enrichment of elements heavier than the iron group. Such galaxies are not found among the surviving UFD galaxies whose chemistry has been studied. With the exception of Ba II in Segue 1, Sr II and Ba II lines have been detected in giants in each of the lowest luminosity dwarf galaxies studied, Leo IV ($M_V = −5.8$), Ursa Major II ($M_V = −4.2$), Coma Berenices ($M_V = −4.1$), and Segue 1 ($M_V = −1.5$) (Frebel et al. 2010a; Norris et al. 2010b; Simon et al. 2010). All galax-

ies examined to date show the presence of heavy elements.

Both Sr II resonance lines have been detected in the most iron-poor star known, HE 1327−2326 (Frebel et al. 2005). The three other known iron-poor stars with [Fe/H] < −4.5 yield only upper limits on [Sr/H], but these upper limits are all significantly lower than the [Sr/H] ratio found in HE 1327−2326. This cosmic dispersion at the lowest levels of [Fe/H] was first pointed out by Aoki et al. (2006) when less data were available, and it still holds true with current data. The [Sr/H] limits in HE 0107−5240 (Christlieb et al. 2004) and HE 0557−4840 (Norris et al. 2007) are among the lowest found for any star, with the exception of HE 1116−0634 as noted above. The [Sr/H] upper limit given by Caffau et al. (2012) for SDSS J102915+172927, [Sr/H] < −5.1, is a factor of a few higher than these stars. Nevertheless, the detection of Sr II lines in HE 1327−2326 indicates that at least one mechanism to produce elements heavier than the iron group can operate at the extremely low metallicities of the stars that enriched the most iron-poor stars. Ba II lines have not been detected in any of these stars, and the present upper limits are not low enough to be of great interest.

7. NUCLEOSYNTHESIS OF STRONTIUM AND BARIUM

Neutron-capture reactions are the only known mechanisms for production of elements heavier than the second neutron-capture peaks ($130 \lesssim A \lesssim 140$). Charged particle reactions may be able to produce elements near the first peaks, like strontium, but they are unable to produce elements at or beyond the second peaks, including barium, as shown by the calculations of, e.g., Farouqi et al. (2010). The presence of barium and any heavier elements, including europium, indicates the operation of some kind of neutron-capture reaction.

Although the abundances of strontium and barium are considerably lower in halo stars than the abundances of lighter elements like magnesium, calcium, or iron, the current data indicate that these heavy elements may be found in nearly every star. This raises the intriguing prospect that at least one kind of neutron-capture reaction operates as frequently as the nucleosynthesis mechanisms that produce the lighter elements in the early Universe. The yields of the heavy elements must certainly be variable and decoupled from the production of magnesium and iron to explain the observed small dispersion in [Mg/Fe] and large dispersion in [Eu/Fe]. The mass ranges of the supernovae that provide this enrichment must also play an important role, since there is evidence that some stars may have been enriched by very few or just one massive supernova (e.g., Simon et al. 2010). Detailed chemical evolution models to test this scenario are beyond the goals of the present study.

8. IMPROVING THE OBSERVATIONS

The detection thresholds indicate that, in principle, there is still room for improvement in constraining the upper limits on [Sr/H] and [Ba/H] in cool giants. Using the relationships between the equivalent width, signal-to-noise (S/N), and spectrograph parameters given by Cayrel (1988) or Frebel et al. (2008), it is possible to quantify how much improvement could be expected. The workhorse high-resolution echelle spectrographs on the largest optical telescopes are MIKE on the Magellan-Clay Telescope (Bernstein et al. 2003), UVES on the Very Large Telescope (Dekker et al. 2000), HRS on the Hobby-Eberly Telescope (Tull 1998), HDS on the Subaru Telescope (Noguchi et al. 2002), and HIRES on the Keck I Telescope (Vogt et al. 1994). For standard high-resolution settings ($R \sim$ 30,000 to 50,000) on these instruments, 3σ upper limits at S/N $\sim$ 50 pixel^{-1} are approximately 3 mÅ to 5 mÅ at the Sr II and Ba II resonance lines.

Obtaining spectra of this quality of cool giants in distant dwarf galaxies is challenging since Segue 1, Ursa Major II, Coma Berenices, Draco, Hercules and Leo IV are located at distances of 23 ± 2 kpc (Belokurov et al. 2007), 30 ± 5 kpc (Zucker et al. 2006), 44 ± 4 kpc (Belokurov et al. 2007), 76 ± 6 kpc (Bonanos et al. 2004), 132 ± 12 kpc (Coleman et al. 2007), and 154 ± 5 kpc (Moretti et al. 2009), respectively. For example, Fulbright et al. (2004) integrated 10 h with HIRES on Star 119 in Draco to obtain S/N ~ 35 pixel^{-1} at the Ba II resonance lines and 4.2 h to obtain S/N ~ 7 pixel^{-1} at the Sr II resonance lines.

Additional higher-excitation lines of Ba II are found at redder wavelengths (5853, 6141, and 6496 Å). These lines are intrinsically weaker than the resonance Ba II lines in cool stars, but they are useful because of the increased stellar flux and S/N attainable at these wavelengths in comparable exposure times. Some of the results shown in Figure 3 (e.g., stars in the Hercules dwarf; Koch et al. 2008) are derived from these lines.

Fortunately, many of the field giants shown in Figures 1–3 are within ≈ 10 kpc of the Sun, so high S/N ratios in the blue spectral region are attainable. With deliberate effort to achieve higher S/N ratios in the blue (50–100 pixel^{-1}), levels of strontium and barium lower by factors of two to three could be detected. Should giants exist with even lower [Sr/H] or [Ba/H] ratios, the present suite of spectrographs on 6–10 m class telescopes is capable of identifying them.

9. CONCLUSIONS

The main result of this study is that no metal-poor stars have yet been found with sufficiently low limits on [Sr/H] or [Ba/H] to suggest their birth environment had not been enriched by elements heavier than the iron group. Sr II and Ba II lines are always detected in cool globular cluster and field stars when studied with high-quality observations. A few stars in some of the low-luminosity dwarf galaxies may have been born in the regions most lacking in heavy elements, but strontium and barium have been detected in at least a few stars in all dwarf galaxies yet studied.

The identification of stars with unusually low [Sr/H] or [Ba/H] would, of course, be of great interest. Current upper limits can be improved by observational campaigns dedicated to improving the S/N ratios at the blue wavelengths where the Sr II and Ba II resonance lines are found. In cool giants, upper limits on [Sr/H] and [Ba/H] that are better by factors of two to three are attainable with current instruments.

One goal moving forward is to test whether all regions where low-mass stars formed in and around the halo of the Milky Way have experienced at least mini-

mal amounts of enrichment with elements heavier than the iron group. Whatever the outcome, this will have profound implications for characterizing the frequency and environmental influence of the astrophysical sites of heavy element production.

APPENDIX

ADDITIONAL COMMENTS ON THE LITERATURE SAMPLE

Repeat observations of the same star by different investigators are quite common. In general I have adopted the results derived from the higher quality spectra, and I have avoided mixing abundance ratios reported by different investigators for the same star. There are two cases where one study reported a detection of Sr II but not Ba II, but another study reported a detection of Ba II but not Sr II. For these stars, G64–37 (Aoki et al. 2009a; Ishigaki et al. 2010) and HD 184499 (Fulbright 2000; Mishenina & Kovtyukh 2001), I have included both detections.

For one star, CS 22949–048, I include the non-LTE abundances of [Sr/H] and [Ba/H]. McWilliam (1998) and Lai et al. (2007) each cite upper limits on [Ba/Fe] in this star, but Andrievsky et al. (2011) report a detection of Ba II and an abundance derived from (only) non-LTE calculations. The [Sr/Fe] and [Ba/Fe] ratios in this star are subsolar but otherwise unremarkable.

Lai et al. (2007) reported abundances for CS 22962–006. This star was misidentified and should instead be classified as a white dwarf (D. Lai, 2012, private communication). Consequently this star is not included in the present sample.

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